CLAIMS

We claim:

1. A micro-electro-mechanical optical apparatus comprising:

an optical element capable of motion in at least one degree of freedom wherein the motion in the at least one degree of freedom is enabled by serpentine hinges configured to enable the optical element to move in the at least one degree of freedom;

driving elements configured to deflect the optical element in said at least one degree of freedom to controllably induce deflection in the optical element; and

damping element.

2. The micro-electro-mechanical optical apparatus of Claim 1 wherein the optical element is constructed of single crystal silicon.

3. The micro-electro-mechanical optical apparatus of Claim 1 wherein

the optical element is capable of motion in two degrees of freedom;

and wherein the two degrees of freedom are enabled by a first pair of serpentine hinges configured to enable the optical element to move in one degree of freedom and a second pair of serpentine hinges configured to enable the optical element to move in a second degree of freedom; and

wherein the driving elements are configured to deflect the optical element in said two degrees of freedom.

4. The micro-electro-mechanical optical apparatus of Claim 1 wherein said damping element comprises a damping means.

5. The micro-electro-mechanical optical apparatus of Claim 1 wherein said damping element comprises a coating of a damping agent applied to the serpentine hinges.

6. The micro-electro-mechanical optical apparatus of Claim 1 wherein said damping element comprises the serpentine hinges configured to reduce magnitude of resonances.

7. A micro-electro-mechanical optical apparatus as in Claim 1 wherein the optical element includes at least one reflective surface.

8. A reflector array comprising a plurality of micro-electro-mechanical optical apparatus as described in Claim 2.

9. A micro-electro-mechanical optical apparatus as in Claim 1 wherein the at least one degree of freedom is further enabled by at least one pair of torsional hinges.

10. A micro-electro-mechanical optical apparatus as in Claim 1 wherein the optical apparatus is incorporated into a wavelength router having an optical cross-connect switch and a wavelength division multiplexer.

11. A micro-electro-mechanical optical apparatus comprising:

a support structure having a plurality of optical device assemblies formed thereon, wherein the optical device assemblies include:

a movable optical element having an outside edge joined to the support structure using a pair of serpentine hinges;

driving elements positioned such that activation of the driving elements can controllably induce deflection in the movable optical element; and

a damping element.

12. A plurality of micro-electro-mechanical optical apparatuses as in Claim 11 wherein the movable optical element is formed having a thickness and the pair of serpentine hinges are formed having a hinge thickness and wherein the hinge thickness is substantially the same thickness as the thickness of the movable optical element.

13. A plurality of micro-electro-mechanical optical apparatuses as in Claim 11 wherein the movable optical element is formed having a thickness and the pair of serpentine hinges

are formed having a hinge thickness and wherein the hinge thickness is thinner than the thickness of the movable optical element.

14. A plurality of micro-electro-mechanical optical apparatuses as in Claim 11 wherein the plurality of micro-electro-mechanical optical apparatuses are organized in a two dimensional MxN array.

15. A micro-electro-mechanical optical apparatus as in Claim 11 wherein the movable optical element comprises a mirror having at least one reflective surface.

16. A micro-electro-mechanical optical apparatus as in Claim 11 wherein the movable optical element is selected from a group consisting of filters, blockers, gratings and lenses.

17. A micro-electro-mechanical optical apparatus as in Claim 15 wherein the damping element comprises a damping agent means.

18. A micro-electro-mechanical optical apparatus as in Claim 15 wherein the damping element comprises a layer of a damping agent formed on the pair of serpentine hinges.

19. A micro-electro-mechanical optical apparatus as in Claim 18 wherein the damping agent comprises a polymeric material.

20. A micro-electro-mechanical optical apparatus as in Claim 15 wherein the serpentine hinges comprise at least one winding with each winding having two arms.

21. A micro-electro-mechanical optical apparatus as in Claim 20 wherein each arm of each winding of each serpentine hinge extends in a direction transverse to an axis of rotation defined by the pair of serpentine hinges.

22. A micro-electro-mechanical optical apparatus as in Claim 20 wherein each arm of each winding of each serpentine hinge extends in a direction transverse to the axis of rotation

defined by the pair of serpentine hinges and wherein each arm is generally contoured to coincide with the shape of the outside edge of the mirror thereby defining circumferentially curved serpentine hinges.

23. A micro-electro-mechanical optical apparatus as in Claim 15 wherein the serpentine hinges comprise at least one winding with each winding having two arms and wherein a proximal portion of each arm of each winding of each serpentine hinge includes a proximal fold which shapes the proximal portion of each arm such that it extends in a direction substantially parallel to an axis of rotation defined by the pair of serpentine hinges.

24. A micro-electro-mechanical optical apparatus as in Claim 15 wherein the shape of the pair of serpentine hinges comprises the damping element.

25. A micro-electro-mechanical optical apparatus as in Claim 24 wherein each of the serpentine hinges further comprise:

at least one winding with each winding having two arms with each winding having a length;

one end of each serpentine hinge is connected to the movable optical element and another end of the serpentine hinge is connected to the support structure; and

the length of each winding becomes progressively shorter from the one end of each serpentine hinge to the another end of each serpentine hinge.

26. A micro-electro-mechanical optical apparatus as in Claim 24 wherein each of the serpentine hinges further comprise:

at least one winding with each winding having two arms with each winding having a length;

one end of each serpentine hinge is connected to the movable optical element and another end of the serpentine hinge is connected to the support structure; and

the length of each winding becomes progressively longer from the one end of each serpentine hinge to the another end of each serpentine hinge.

27. A micro-electro-mechanical optical apparatus comprising:

a support structure having a plurality of bi-axial optical device assemblies formed thereon, wherein the bi-axial optical device assemblies include:

a movable frame element having an inside periphery and an outside periphery;

the outside periphery of the movable frame element joined to the support structure using a first pair of serpentine hinges, the first pair of serpentine hinges defining a first axis of rotation about which the movable frame element can rotate;

a movable optical element having an outside periphery;

the outside periphery of the movable optical element joined to the movable frame element using a second pair of serpentine hinges, the second pair of serpentine hinges defining a second axis of rotation about which the movable optical element can rotate;

frame driving elements positioned such that activation of the frame driving elements can controllably induce deflection in the movable frame element, said deflection inducing rotation of the movable optical element about the first axis of rotation defined by the first pair of serpentine hinges;

optical element driving elements positioned such that activation of the optical element driving elements can controllably induce deflection in the movable optical element, said deflection inducing rotation of the movable optical element about the second axis of rotation defined by the second pair of serpentine hinges; and

a damping element.

28. A plurality of micro-electro-mechanical optical apparatuses as in Claim 27 wherein a plurality of bi-axial optical device assemblies are organized in a two dimensional MxN array of micro-electro-mechanical optical apparatuses.

29. A micro-electro-mechanical optical apparatus as in Claim 27 wherein the first axis of rotation about which the movable frame element can rotate is transverse to the second axis of rotation about which the movable optical element can rotate.

30. A micro-electro-mechanical optical apparatus as in Claim 27 wherein the first axis of rotation about which the movable frame element can rotate is at substantially right angle to the second axis of rotation about which the movable optical element can rotate.

31. A micro-electro-mechanical optical apparatus as in Claim 27 wherein the movable optical element comprises a mirror having at least one reflective surface.

32. A micro-electro-mechanical optical apparatus as in Claim 27 wherein the movable optical element is selected from a group consisting of filters, blockers, gratings and lenses.

33. A micro-electro-mechanical optical apparatus as in Claim 31 wherein the damping element comprises a damping means.

34. A micro-electro-mechanical optical apparatus as in Claim 31 wherein the damping element comprises a layer of a damping agent formed on at least one pair of the first and second pairs of serpentine hinges.

35. A micro-electro-mechanical optical apparatus as in Claim 34 wherein the damping agent comprises a polymeric material.

36. A micro-electro-mechanical optical apparatus as in Claim 31 wherein each of the first and second pairs of serpentine hinges comprise at least one winding with each winding having two arms.

37. A micro-electro-mechanical optical apparatus as in Claim 36 wherein each arm of each winding of each of the first pair of serpentine hinges extends in a direction transverse to the axis of rotation defined by the first pair of serpentine hinges, and

wherein each arm of each winding of each of the second pair of serpentine hinges extends in a direction transverse to the axis of rotation defined by the second pair of serpentine hinges.

38. A micro-electro-mechanical optical apparatus as in Claim 37 wherein each arm of each winding of each first serpentine hinge extends in a direction transverse to the axis of rotation defined by the first pair of serpentine hinges and wherein each arm of the first serpentine hinge is generally contoured to coincide with the shape of the outside periphery of the mirror; and

wherein each arm of each winding of each second serpentine hinge extends in a direction transverse to the axis of rotation defined by the second pair of serpentine hinges and wherein each arm of the second serpentine hinge is generally contoured to coincide with the shape of the outside periphery of the frame element.

39. A micro-electro-mechanical optical apparatus as in Claim 31 wherein each pair of the first and second serpentine hinges comprise at least one winding with each winding having two arms and wherein a proximal portion of each arm of each winding of each serpentine hinge includes a proximal fold which shapes the proximal portion of each arm such that it extends in a direction substantially parallel to the axis of rotation defined by each pair of serpentine hinges.

40. A micro-electro-mechanical optical apparatus as in Claim 31 wherein the shape of the pairs of the first and second serpentine hinges comprise the damping element.

41. A micro-electro-mechanical optical apparatus as in Claim 31 wherein each of the serpentine hinges further comprise:

the first pair of serpentine hinges comprising:

at least one winding with each winding having two arms with each winding having a length;

one end of each first serpentine hinge is connected to the frame element and another end of the serpentine hinge is connected to the support structure; and

the length of each winding becomes progressively shorter from the one end of each first serpentine hinge to the another end of each first serpentine hinge; and

the second pair of serpentine hinges comprising:

at least one winding with each winding having two arms with each winding having a length;

one end of each second serpentine hinge is connected to the frame element and another end of the serpentine hinge is connected to the movable optical element; and

the length of each winding becomes progressively shorter from the one end of each second serpentine hinge to the another end of each second serpentine hinge.

42. A micro-electro-mechanical optical apparatus as in Claim 31 wherein each of the first and second serpentine hinges further comprise:

a first end and a second end;

at least one winding with each winding having two arms with each winding having a length; and

the length of each winding becomes progressively longer from the first end of each serpentine hinge to the second end of each serpentine hinge.

43. A micro-electro-mechanical optical apparatus comprising:

a support structure having a plurality of bi-axial optical device assemblies formed thereon, wherein the bi-axial optical device assemblies include:

a first movable frame element having an inside periphery and an outside periphery;

a second movable frame element having an inside periphery and an outside periphery;

a third movable frame element having an inside periphery and an outside periphery;

a movable optical element having an outside periphery;

the outside periphery of the first movable frame element joined to the support structure using a first pair of serpentine hinges, the first pair of serpentine hinges defining a first axis of rotation about which the first movable frame element can rotate;

the outside periphery of the second movable frame element joined to the inside periphery of the first movable frame using a first pair of torsional hinges which defines a first torsional axis of rotation about which the second movable frame element can rotate, the first

torsional axis of rotation is substantially parallel to the first axis of rotation about which the first movable frame element can rotate;

the outside periphery of the third movable frame element joined to the inside periphery of the second movable frame using a second pair of serpentine hinges which define a second axis of rotation about which the third movable frame element can rotate, the second axis of rotation being transverse to the first axis of rotation;

the outside periphery of the movable optical element joined to the third movable frame element using a second pair of torsional hinges which defines a second torsional axis of rotation about which the optical element can rotate, the second torsional axis of rotation is transverse to the first axis of rotation and to the first torsional axis of rotation;

first frame driving elements positioned such that activation of the first frame driving elements can controllably induce deflection in the first movable frame element, said deflection inducing rotation of the first movable optical element about the first axis of rotation defined by the first pair of serpentine hinges;

second frame driving elements positioned such that activation of the second frame driving elements can controllably induce deflection in the second movable frame element, said deflection inducing rotation of the second movable optical element about the first torsional axis of rotation defined by the first pair of torsional hinges;

third frame driving elements positioned such that activation of the third frame driving elements can controllably induce deflection in the third movable frame element, said deflection inducing rotation of the third movable frame element about the second axis of rotation defined by the second pair of serpentine hinges;

optical element driving elements positioned such that activation of the optical element driving elements can controllably induce deflection in the movable optical element, said deflection inducing rotation of the movable optical element about the second torsional axis of rotation defined by the second pair of torsional hinges; and

a damping element.

44. A micro-electro-mechanical optical apparatus as in Claim 43 wherein the movable optical element comprises a mirror having at least one reflective surface.

45. A plurality of micro-electro-mechanical optical apparatuses as in Claim 44 wherein the plurality of micro-electro-mechanical optical apparatuses define reflector assemblies and wherein the reflector assemblies are organized in a two dimensional MxN reflector array.

46. A micro-electro-mechanical optical apparatus as in Claim 43 wherein the movable optical element is selected from a group consisting of filters, blockers, gratings, and lenses.

47. A micro-electro-mechanical optical apparatus as in Claim 44 wherein the damping element comprises a layer of a damping agent formed on at least one of the first and second pairs of serpentine hinges and first and second pairs of torsional hinges.

48. A micro-electro-mechanical optical apparatus as in Claim 47 wherein the damping agent comprises a polymeric material.

49. A micro-electro-mechanical optical apparatus as in Claim 44 wherein each of the first and second pairs of serpentine hinges comprise at least one winding with each winding having two arms.

50. A micro-electro-mechanical optical apparatus as in Claim 49 wherein each arm of each winding of each of the first pair of serpentine hinges extends in a direction transverse to the axis of rotation defined by the first pair of serpentine hinges, and

wherein each arm of each winding of each of the second pair of serpentine hinges extends in a direction transverse to the axis of rotation defined by the second pair of serpentine hinges.

51. A micro-electro-mechanical optical apparatus as in Claim 50 wherein each arm of each winding of each first serpentine hinge extends in a direction transverse to the axis of rotation defined by the first pair of serpentine hinges and wherein each arm of the first serpentine hinge is generally contoured to coincide with the shape of the outside periphery of the mirror; and

wherein each arm of each winding of each second serpentine hinge extends in a direction transverse to the axis of rotation defined by the second pair of serpentine hinges and wherein each arm of the second serpentine hinge is generally contoured to coincide with the shape of the outside periphery of the frame element.

52. A micro-electro-mechanical optical apparatus comprising in combination:

a support structure;

a movable optical element

at least one pair of serpentine hinges;

driving elements positioned such that activation of the driving elements can controllably induce deflection in the movable optical element;

a damping element; and

the combination comprising means for inducing a damped rotation of the movable optical element about an axis of rotation defined by each of the at least one pair of serpentine hinges.

53. The micro-electro-mechanical optical apparatus of claim 52 wherein the movable optical element comprises a bi-axial reflector element movable in two substantially perpendicular axes defined by the at least one pair of serpentine hinges wherein the at least one pair of serpentine hinges comprises a first pair of serpentine hinges defining a first axis of the two substantially perpendicular axes and a second pair of serpentine hinges defining a second axis of the two substantially perpendicular axes.

54. The micro-electro-mechanical optical apparatus of claim 53 wherein a plurality of said movable optical elements comprises a reflector array incorporated into a single reflector array optical switching device.

55. The micro-electro-mechanical optical apparatus of claim 53 wherein a plurality of said movable optical elements are incorporated into a pair of reflector arrays used in a two reflector array optical switching device.

56. A method for forming an array of MEMS optical elements comprises:

providing a single crystal silicon on insulator (SOI) wafer having a layered structure comprising a silicon wafer layer having an internal oxide layer formed thereon and having a device silicon layer formed on the internal oxide layer, wherein a top surface of the device silicon layer has formed thereon a top oxide layer, and wherein the bottom surface of the silicon wafer layer has formed thereon bottom oxide layer;

forming a bottom photoresist layer on the bottom oxide film layer having openings defining a bottom pocket;

forming a top photoresist layer on the top oxide film layer having openings defining hinge regions and open structures;

first etching to remove the top oxide layer in hinge and open regions defined by the openings in the top photoresist layer exposing a hinge region of the device silicon layer;

forming a second photoresist layer on a top surface of the SOI wafer, the second photoresist layer patterning the hinge region of the device silicon layer so that a hinge can be formed;

second etching the patterned hinge and open region to remove portions of the device silicon layer forming recessed portions and such that unetched surfaces correspond to a hinge;

removing the second photoresist layer, thereby exposing the underlying top oxide layer as a hard mask layer having openings in the hinge and open regions;

third etching the device silicon layer through the openings in the hard mask wherein the recessed portions are etched until the internal oxide layer is reached, and wherein the unetched surfaces are partially etched leaving a portion of the unetched surfaces in place as hinges, thereby defining hinge thickness;

fourth etching the bottom surface of the SOI wafer through openings in the bottom oxide layer to remove material from the silicon wafer layer to form a pocket region defining a movable optical element supported by hinges;

fifth etching the SOI wafer to remove the internal oxide layer in the pocket region; and

forming a reflective layer on at least one surface of the movable optical element.

57 The method of Claim 56 further including a sixth etching to remove material from a separation line region thereby enabling the structure to be separated into arrays of a desired size.

58. The method of Claim 57 wherein the operation of sixth etching comprises the operations of:

dry etching to remove material from the separation line region;

laser cutting in the separation line region; and

cleaving in the separation line region into separate arrays of desired sizes.

59 The method of Claim 57 wherein the operation of sixth etching comprises the operations of:

laser cutting in the separation line region; and

cleaving in the separation line region into separate arrays of desired sizes.

60 The method of Claim 57 wherein the operation of sixth etching comprises the operations of:

dry etching to remove material from the separation line region; and

cleaving in the separation line region into separate arrays of desired sizes.

61. The method of Claim 57 further comprising:

assembling the separated arrays with another wafer having formed thereon appropriate driving elements and control circuitry, and

packaging the assembled arrays.

62 The method of Claim 61 wherein packaging the assembled arrays comprises hermetically packaging the assembled arrays.

63. A method for forming an array of MEMS optical elements comprises:

providing a single crystal silicon wafer having top surface and a bottom surface, the top surface having formed thereon a top oxide layer and the bottom surface having formed thereon a bottom oxide layer;

forming a bottom photoresist layer on the bottom oxide film layer having openings defining a bottom pocket;

forming a top photoresist layer on the top oxide film layer having openings defining hinge regions and open structures;

first etching to remove the top oxide layer in hinge and open regions defined by the openings in the top photoresist layer exposing a hinge region of the device silicon layer;

forming a second photoresist layer on a top surface of the wafer, the second photoresist layer patterning the hinge region of the device silicon layer so that a hinge can be formed;

second etching the patterned hinge and open region to remove portions of the device silicon layer in a timed etch, thereby forming recessed portions and such that unetched surfaces correspond to a hinge;

removing the second photoresist layer, thereby exposing the underlying top oxide layer as a hard mask layer having openings in the hinge and open regions;

third etching the device silicon layer through the openings in the hard mask wherein the recessed portions are etched in a timed etch leaving a portion of the unetched surfaces in place as hinges, thereby defining hinge thickness;

fourth etching the bottom surface of the SOI wafer through openings in the bottom oxide layer to remove material from the silicon wafer to form a pocket region defining a movable optical element supported by hinges; and

forming a reflective layer on at least one surface of the movable optical element.

64. The method of Claim 63 further including a fifth etching to remove material from a separation line region thereby enabling the structure to be separated into arrays of a desired size.

65. The method of Claim 64 wherein the operation of fifth etching comprises the operations of:

dry etching to remove material from the separation line region;

laser cutting in the separation line region; and

cleaving in the separation line region into separate arrays of desired sizes.

66. The method of Claim 64 wherein the operation of sixth etching comprises the operations of:

laser cutting in the separation line region; and

cleaving in the separation line region into separate arrays of desired sizes.

67. The method of Claim 64 wherein the operation of sixth etching comprises the operations of:

dry etching to remove material from the separation line region; and

cleaving in the separation line region into separate arrays of desired sizes.

68. The method of Claim 64 further comprising:

assembling the separated arrays with another wafer having formed thereon appropriate driving elements and control circuitry, and

packaging the assembled arrays.